

1           Fitness tracking reveals task-specific associations  
2           between memory, mental health, and exercise

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8           **Abstract**

9           Physical exercise can benefit both physical and mental well-being. Different forms of exercise  
10          (i.e., aerobic versus anaerobic; running versus walking versus swimming versus yoga; high-  
11          intensity interval training versus endurance workouts; etc.) impact physical fitness in different  
12          ways. For example, running may substantially impact leg and heart strength but only moderately  
13          impact arm strength. We hypothesized that the mental benefits of exercise might be similarly  
14          differentiated. We focused specifically on how different forms of exercise might relate to different  
15          aspects of memory and mental health. To test our hypothesis, we collected nearly a century's  
16          worth of fitness data (in aggregate). We then asked participants to fill out surveys asking them  
17          to self-report on different aspects of their mental health. We also asked participants to engage in  
18          a battery of memory tasks that tested their short and long term episodic, semantic, and spatial  
19          memory. We found that participants with similar exercise habits and fitness profiles tended to  
20          also exhibit similar mental health and task performance profiles.

<sup>21</sup> **Introduction**

<sup>22</sup> Engaging in physical activity (exercise) can improve our physical fitness by increasing muscle  
<sup>23</sup> strength (Crane et al., 2013; Knuttgen, 2007; Lindh, 1979; Rogers and Evans, 1993), increasing bone  
<sup>24</sup> density (Bassey and Ramsdale, 1994; Chilibeck et al., 2012; Layne and Nelson, 1999), increasing  
<sup>25</sup> cardiovascular performance (Maiorana et al., 2000; Pollock et al., 2000), increasing lung capac-  
<sup>26</sup> ity (Lazovic-Popovic et al., 2016) (although see Roman et al., 2016), increasing endurance (Wilmore  
<sup>27</sup> and Knuttgen, 2003), and more. Exercise can also improve mental health (Basso and Suzuki, 2017;  
<sup>28</sup> Callaghan, 2004; Deslandes et al., 2009; Mikkelsen et al., 2017; Paluska and Schwenk, 2000; Raglin,  
<sup>29</sup> 1990; Taylor et al., 1985) and cognitive performance (Basso and Suzuki, 2017; Brisswalter et al.,  
<sup>30</sup> 2002; Chang et al., 2012; Ettnier et al., 2006).

<sup>31</sup> The physical benefits of exercise can be explained by stress-responses of the affected body tis-  
<sup>32</sup> sues. For example, skeletal muscles that are taxed during exercise exhibit stress responses (Morton  
<sup>33</sup> et al., 2009) that can in turn affect their growth or atrophy (Schiaffino et al., 2013). By comparison,  
<sup>34</sup> the benefits of exercise on mental health are less direct. For example, one hypothesis is that ex-  
<sup>35</sup> ercise leads to specific physiological changes, such as increased aminergic synaptic transmission  
<sup>36</sup> and endorphin release, which in turn act on neurotransmitters in the brain (Paluska and Schwenk,  
<sup>37</sup> 2000).

<sup>38</sup> Speculatively, if different exercise regimens lead to different neurophysiological responses, one  
<sup>39</sup> might be able to map out a spectrum of signalling and transduction pathways that are impacted  
<sup>40</sup> by a given type, duration, and intensity of exercise in each brain region. For example, prior work  
<sup>41</sup> has shown that exercise increases acetylcholine levels, starting in the vicinity of the exercised  
<sup>42</sup> muscles (Shoemaker et al., 1997). Acetylcholine is thought to play an important role in memory  
<sup>43</sup> formation (Palacios-Filardo et al., 2021, e.g., by modulating specific synaptic inputs from entorhinal  
<sup>44</sup> cortex to the hippocampus, albeit in rodents). Given the central role of these medial temporal  
<sup>45</sup> lobe structures play in memory, changes in acetylcholine might lead to specific changes in memory  
<sup>46</sup> formation and retrieval.

<sup>47</sup> In the present study, we hypothesize that (a) different exercise regimens will have different,

48 quantifiable impacts on cognitive performance and mental health, and that (b) these impacts will  
49 be consistant across individuals. To this end, we collected a year of fitness tracking data from  
50 each of 113 participants. We then asked each participant to fill out a brief survey in which they  
51 self-evaluated several aspects of their mental health. Finally, we ran each participant through a  
52 battery of memory tasks, which we used to evaluate their memory performance along several  
53 dimensions. We examined the data for potential associations between memory, mental health, and  
54 exercise.

## 55 **Methods**

56 We ran an online experiment using the Amazon Mechanical Turk platform. We collected data  
57 about each participant’s fitness and exercise habits, a variety of self-reported measures concerning  
58 their mental health, and about their performance on a battery of memory tasks. We mined the  
59 dataset for potential associations between memory, mental health, and exercise.

## 60 **Experiment**

### 61 **Participants**

62 We recruited experimental participants by posting our experiment as a Human Intelligence Task  
63 (HIT) on the Amazon Mechanical Turk platform. We limited participation to Mechanical Turk  
64 Workers who had been assigned a “Masters” designation on the platform, given to workers who  
65 score highly across several metrics on a large number of HITs, according to a proprietary algorithm  
66 managed by Amazon. We further limited our participant pool to participants who self-reported that  
67 they were fluent in English and regularly used a Fitbit fitness tracker device. A total of 160 workers  
68 accepted our HIT in order to participate in our experiment. Of these, we excluded all participants  
69 who failed to log into their Fitbit account (giving us access to their anonymized fitness tracking  
70 data), encountered technical issues (e.g., by accessing the HIT using an incompatible browser,  
71 device, or operating system), or who ended their participation prematurely, before completing the

72 full study. In all, 113 participants remained that contributed usable data to the study.

73 For their participation, workers received a base payment of \$5 per hour (computed in 15  
74 minute increments, rounded up to the nearest 15 minutes), plus an additional performance-based  
75 bonus of up to \$5. Our recruitment procedure and study protocol were approved by Dartmouth's  
76 Committee for the Protection of Human Subjects.

77 **Gender, age, and race.** Of the 113 participants who contributed usable data, 77 reported their  
78 gender as female, 35 as male, and 1 chose not to report their gender. Participants ranged in age  
79 from 19–68 years old (25<sup>th</sup> percentile: 28.25 years; 50<sup>th</sup> percentile: 32 years; 75<sup>th</sup> percentile: 38  
80 years). Participants reported their race as White (90 participants), Black or African American (11  
81 participants), Asian (7 participants), Other (4 participants), and American Indian or Alaska Native  
82 (3 participants). One participant opted not to report their race.

83 **Languages.** All participants reported that they were fluent in either 1 and 2 languages (25<sup>th</sup>  
84 percentile: 1; 50<sup>th</sup> percentile: 1; 75<sup>th</sup> percentile: 1), and that they were "familiar" with between 1  
85 and 11 languages (25<sup>th</sup> percentile: 1; 50<sup>th</sup> percentile: 2; 75<sup>th</sup> percentile: 3).

86 **Reported medical conditions and medications.** Participants reported having and/or taking med-  
87 ications pertaining to the following medical conditions: anxiety or depression (4 participants),  
88 recent head injury (2 participants), high blood pressure (1 participant), bipolar (1 participant),  
89 hypothyroidism (1 participant), and other unspecified medications (1 participant). Participants  
90 reported their current and typical stress levels on a Likert scale as very relaxed (-2), a little relaxed  
91 (-1), neutral (0), a little stressed (1), or very stressed (2). The "current" stress level reflected par-  
92 ticipants' stress at the time they participated in the experiment. Their responses ranged from -2  
93 to 2 (current stress: 25<sup>th</sup> percentile: -2; 50<sup>th</sup> percentile: -1; 75<sup>th</sup> percentile: 1; typical stress: 25<sup>th</sup>  
94 percentile: 0; 50<sup>th</sup> percentile: 1; 75<sup>th</sup> percentile: 1). Participants also reported their current level of  
95 alertness on a Likert scale as very sluggish (-2), a little sluggish (-1), neutral (0), a little alert (1),  
96 or very alert (2). Their responses ranged from -2 to 2 (25<sup>th</sup> percentile: 0; 50<sup>th</sup> percentile: 1; 75<sup>th</sup>  
97 percentile: 2). Nearly all (111 out of 113) participants reported that they had normal color vision,

98 and 15 participants reported uncorrected visual impairments (including dyslexia and uncorrected  
99 near- or far-sightedness).

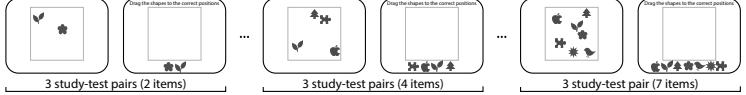
100 **Residence and level of education.** Participants reported their residence as being located in the  
101 suburbs (36 participants), a large city (30 participants), a small city (23 participants), rural (14 partic-  
102 ipants), or a small town (10 participants). Participants reported their level of education as follows:  
103 College graduate (42 participants), Master's degree (23 participants), Some college (21 partici-  
104 pants), High school graduate (9 participants), Associate's degree (8 participants), Other graduate  
105 or professional school (5 participants), Some graduate training (3 participants), or Doctorate (2  
106 participants).

107 **Reported water and coffee intake.** Participants reported the number of cups of water and coffee  
108 they had consumed prior to accepting the HIT. Water consumption ranged from 0–6 cups (25<sup>th</sup>  
109 percentile: 1; 50<sup>th</sup> percentile: 3; 75<sup>th</sup> percentile: 4). Coffee consumption ranged from 0–4 cups (25<sup>th</sup>  
110 percentile: 0; 50<sup>th</sup> percentile: 1; 75<sup>th</sup> percentile: 2).

## 111 **Tasks**

112 Upon accepting the HIT posted on Mechanical Turk, the worker was directed to read and fill out  
113 a screening and consent form, and to share access to their anonymized Fitbit data via their Fitbit  
114 account. After consenting to participate and successfully sharing their Fitbit data, participants  
115 filled out a survey and then engaged in a series of memory tasks (Fig. 1). All stimuli and code for  
116 running the full Mechanical Turk experiment may be found [here](#).

117 **Survey questions.** We collected the following demographic information from each participant:  
118 their birth year, gender, highest (academic) degree achieved, race, language fluency, and language  
119 familiarity. We also collected information about participants' health and wellness, including about  
120 their vision, alertness, stress, sleep, coffee and water consumption, location of their residence,  
121 activity typically required for their job, and exercise habits.

	Main task and immediate memory test				Delayed memory test
a.	1 Free recall	Study words 	Memory test 		5 
b.	2 Naturalistic recall	Watch a short video (The Temple of Knowledge)  Video clip plays	Memory tests Free response Multiple choice		6  Free response
c.	3 Foreign language flashcards	Study flashcards 	Memory test Multiple choice		7  Multiple choice
d.	4 Spatial learning	Memorize the positions of increasing numbers of shapes 			N/A

**Figure 1: Battery of memory tasks.** **a. Free recall.** Participants study 16 words (presented one at a time), followed by an immediate memory test where they type each word they remember from the just-studied list. In the delayed memory test, participants type any words they remember studying, from any list. **b. Naturalistic recall.** Participants watch a brief video, followed by two immediate memory tests. The first test asks participants to write out what happened in the video. The second test has participants answer a series of multiple choice questions about the conceptual content of the video. In the delayed memory test, participants (again) write out what happened in the video. **c. Foreign language flashcards.** Participants study a sequence of 10 English-Gaelic word pairs, each presented with an illustration of the given word. During an immediate memory test, participants perform a multiple choice test where they select the Gaelic word that corresponds to the given photograph. During the delayed memory test, participants perform a second multiple choice test, where they select the Gaelic word that corresponds to each of a new set of photographs. **d. Spatial learning.** In each trial, participants study a set of randomly positioned shapes. Next, the shapes' positions are altered, and participants are asked to drag the shapes back to their previous positions. **All panels.** The gray numbers denote the order in which participants experienced each task or test.

<sup>122</sup> **Free recall (Fig. 1a).** Participants studied a sequence of four word lists, each comprising 16 words.  
<sup>123</sup> After studying each list, participants received an immediate memory test, whereby they were asked  
<sup>124</sup> to type (one word at a time) any words they remembered from the just-studied list, in any order.

<sup>125</sup> Words were presented for 2 s each, in black text on a white background, followed by a 2 s blank  
<sup>126</sup> (white) screen. After the final 2 s pause, participants were given 90 s to type in as many words  
<sup>127</sup> as they could remember, in any order. The memory test was constructed such that the participant  
<sup>128</sup> could only see the text of the current word they were typing; when they pressed any non-letter  
<sup>129</sup> key, the current word was submitted and the text box they were typing in was cleared. This was  
<sup>130</sup> intended to prevent participants from retroactively editing their previous responses.

<sup>131</sup> The word lists participants studied were drawn from the categorized lists reported in Ziman  
<sup>132</sup> et al. (2018). Each participant was assigned four unique randomly chosen lists (in a randomized  
<sup>133</sup> order), selected from a full set of 16 lists. Each chosen list was then randomly shuffled before  
<sup>134</sup> presenting the words to the participants.

<sup>135</sup> Participants also performed a final delayed memory test where they were given 180 s to type  
<sup>136</sup> out any words they remembered from *any* of the 4 lists they had studied.

<sup>137</sup> Recalled words within an edit distance of 2 (i.e., a Levenshtein Distance less than or equal to  
<sup>138</sup> 2) of any word in the wordpool were “autocorrected” to their nearest match. We also manually  
<sup>139</sup> corrected clear typos or misspellings by hand (e.g., we corrected “hippopumas” to “hippopota-  
<sup>140</sup> mus”, “zucinni” to “zucchini”, and so on). Finally, we lemmatized each submitted word to match  
<sup>141</sup> the plurality of the matching wordpool word (e.g., “bongo” was corrected to “bongos”, and so  
<sup>142</sup> on). After applying these corrections, any submitted words that matched words presented on the  
<sup>143</sup> just-studied list were tagged as “correct” recalls, and any non-matching words were discarded  
<sup>144</sup> as “errors.” Because participants were not allowed to edit the text they entered, we chose not to  
<sup>145</sup> analyze these putative “errors,” since we could not distinguish typos from true misrememberings.

<sup>146</sup> **Naturalistic recall (Fig. 1b).** Participants watched a 2.5 minute video clip entitled “The Temple  
<sup>147</sup> of Knowledge.” The video comprises an animated story told to StoryCorps by Ronald Clark, who  
<sup>148</sup> was interviewed by his daughter, Jamilah Clark. The narrator (Ronald) discusses growing up

149 living in an apartment over Washington Heights branch of the New York Public Library, where his  
150 father worked as a custodian during the 1940s.

151 After watching the video clip, participants were asked to type out anything they remembered  
152 about what happened in the video. They typed their responses into a text box, one sentence at a  
153 time. When the participant pressed the return key or typed any final punctuation mark (".", "!", or  
154 "?") the text currently entered into the box was "submitted" and added to their transcript, and the  
155 text box was cleared to prevent further editing of any already-submitted text. This was intended to  
156 prevent participants from retroactively editing their previous responses. Participants were given  
157 up to 10 minutes to enter their responses. After 4 minutes participants were given the option of  
158 ending the response period early, e.g., if they felt they had finished entering all of the information  
159 they remembered. Each participant's transcript was constructed from their submitted responses by  
160 combining the sentences into a single document and removing extraneous whitespace characters.

161 Following this 4–10 minute free response period, participants were given a series of 10 multiple  
162 choice questions about the conceptual content of the story. All participants received the same  
163 questions, in the same order.

164 Participants also performed a final delayed memory test, where they carried out the free  
165 response recall task a second time, near the end of the testing session. This resulted in a second  
166 transcript, for each participant.

167 **Foreign language flashcards (Fig. 1c).** Participants studied a series of 10 English-Gaelic word  
168 pairs in a randomized order. We selected the Gaelic language both for its relatively small number of  
169 native speakers and for its dissimilarity to other commonly spoken languages amongst Mechanical  
170 Turk Workers. We verified (via self report) that all of our participants were fluent in English and  
171 that they were neither fluent nor familiar with Gaelic.

172 Each word's "flashcard" comprised a cartoon depicting the given word, the English word or  
173 phrase in lowercase text (e.g., "the boy"), and the Gaelic word or phrase in uppercase text (e.g.,  
174 "BUACHAILL"). Each flashcard was displayed for 4 s, followed by a 3 s interval (during which  
175 the screen was cleared) prior to the next flashcard presentation.

176 After studying all 10 flashcards, participants were given a multiple choice memory test where  
177 they were shown a series of novel photographs, each depicting one of the 10 words they had  
178 learned. They were asked to select which (of 4 unique options) Gaelic word went with the given  
179 picture. The 3 incorrect options were selected at random (with replacement across trials), and the  
180 order in which the choices appeared to the participant were also randomized. Each of the 10 words  
181 they had learned were tested exactly once.

182 Participants also performed a final delayed memory test, where they were given a second set of  
183 10 questions (again, one per word they had studied). For this second set of questions participants  
184 were prompted with a new set of novel photographs, and new randomly chosen incorrect choices  
185 for each question. Each of the 10 original words they had learned were (again) tested exactly once  
186 during this final memory test.

187 **Spatial learning (Fig. 1d).** Participants performed a series of study-test trials where they memo-  
188 rized the onscreen spatial locations of two or more shapes. During the study phase of each trial,  
189 a set of shapes appeared on the screen for 10 s, followed by 2 s of blank (white) screen. During the  
190 test phase of each trial, the same shapes appeared onscreen again, but this time they were vertically  
191 aligned and sorted horizontally in a random order. Participants were instructed to drag (using the  
192 mouse) each shape to its studied position, and then to click a button to indicate that the placements  
193 were complete.

194 In different study-test trials, participants learned the locations of different numbers of shapes  
195 (always drawn from the same pool of 7 unique shapes, where each shape appeared at most one  
196 time per trial). They first performed three trials where they learned the locations of 2 shapes; next  
197 three trials where they learned the locations of 3 shapes; and so on until their last three trials, where  
198 (during each trial) they learned the locations of 7 shapes. All told, each participant performed 18  
199 study-test trials of this spatial learning task (3 trials for each of 2, 3, 4, 5, 6, and 7 shapes).

200 **Fitness tracking using Fitbit devices**

201 To gain access to our study, participants provided us with access to all data associated with their  
202 Fitbit account from the year (365 calendar days) up to and including the day they accepted the HIT.  
203 We filtered out all identifiable information (e.g., participant names, GPS coordinates, etc.) prior to  
204 importing their data.

205 **Collecting and processing Fitbit data**

206 The fitness tracking data associated with participants' Fitbit accounts varied in scope and duration  
207 according to which device the participant owned (Fig. S1), how often the participant wore (and/or  
208 synced) their tracking device, and how long they had owned their device. For example, while all  
209 participants' devices supported basic activity metrics such as daily step counts, only a subset of  
210 the devices with heart rate monitoring capabilities provided information about workout intensity,  
211 resting heart rate, and other related measures.

212 Across all devices, we collected the following information: heart rate data, sleep tracking data,  
213 logged bodyweight measurements, logged nutrition measurements, Fitbit account and device  
214 settings, and activity metrics.

215 **Heart rate.** If available, we extracted all heart rate data collected by participants' Fitbit device(s)  
216 and associated with their Fitbit profile. Depending on the specific device model(s) and settings, this  
217 included second-by-second, minute-by-minute, daily summary, weekly summary, and/or monthly  
218 summary heart rate information. These summaries include information about participants' aver-  
219 age heart rates, and the amount of time they were estimated to have spent in different "heart rate  
220 zones" (rest, out-of-range, fat burn, cardio, or peak, as defined by their Fitbit profile), as well as an  
221 estimate of the number of estimated calories burned while in each heart rate zone.

222 **Sleep.** If available, we extracted all sleep data collected by participants' Fitbit device(s). Depend-  
223 ing on the specific device model(s) and settings, this included nightly estimates of the duration  
224 and quality of sleep, as well as the amount of time spent in each sleep stage (awake, REM, light, or

225 deep).

226 **Weight.** If available, we extracted any weight-related information affiliated with participants'  
227 Fitbit accounts within 1 year prior to enrolling in our study. Depending on their specific device  
228 model(s) and settings, this included their weight, body mass index, and/or body fat percentage.

229 **Nutrition.** If available, we extracted any nutrition-related information affiliated with participants'  
230 Fitbit accounts within 1 year prior to enrolling in our study. Depending on their specific account  
231 settings and usage behaviors, this included a log of the specific foods they had eaten (and logged)  
232 over the past year, and the amount of water consumed each day.

233 **Account and device settings.** We extracted any settings associated with participants' Fitbit ac-  
234 counts to determine (a) which device(s) and model(s) are associated with their Fitbit account, (b)  
235 time(s) when their device(s) were last synced, and (c) battery level(s).

236 **Activity metrics.** If available, we extracted any activity-related information affiliated with par-  
237 ticipants' Fitbit accounts within 1 year prior to enrolling in our study. Depending on their specific  
238 device model(s) and settings, this included: daily step counts; daily amount of time spent in each  
239 activity level (sedentary, lightly active, fairly active, or very active, as defined by their account  
240 settings and preferences); daily number of floors climbed; daily elevation change; and daily total  
241 distance traveled.

242 **Comparing recent versus baseline measurements.**

243 We were interested in separating out potential associations between *absolute* fitness metrics and  
244 *relative* metrics. To this end, in addition to assessing potential raw (absolute) fitness metrics, we  
245 also defined a simple measure of recent changes in those metrics, relative to a baseline:

$$\Delta_{R,B}m = \frac{B \sum_{i=1}^R m(i)}{R \sum_{i=R+1}^{R+B} m(i)},$$

246 where  $m(i)$  is the value of metric  $m$  from  $i - 1$  days prior to testing (e.g.,  $m(1)$  represents the value  
247 of  $m$  on the day the participant accepted the HIT, and  $m(10)$  represents the value of  $m$  9 days prior  
248 to accepting the HIT. Unless otherwise noted, we set  $R = 7$  and  $B = 30$ . In other words, to estimate  
249 recent changes in any metric  $m$ , we divided the average value of  $m$  taken over the prior week by  
250 the average value of  $m$  taken over the 30 days before that.

251 **Exploratory correlation analyses**

252 We used a bootstrap procedure to identify reliable correlations between different memory-related,  
253 fitness-related, and demographic-related variables. For each of  $N = 10,000$  iterations, we selected  
254 (with replacement) a sample of 113 participants to include. This yielded, for each iteration, a  
255 sampled “data matrix” with one row per sampled participant and one column for each measured  
256 variable. When participants were sampled multiple times in a given iteration, as was often the  
257 case, this matrix contained duplicate rows. Next, we computed the Pearson’s correlation between  
258 each pair of columns. This yielded, for each pair of columns, a distribution of  $N$  bootstrapped  
259 correlation coefficients. If fewer than 97.5% of the coefficients for a given pair of columns had the  
260 same sign, we excluded the pair from further analysis and considered the expected correlation  
261 between those columns to be undefined. If  $\geq 97.5\%$  of the coefficients for a given pair of columns  
262 had the same sign (corresponding to a bootstrap-estimated two-tailed  $p$  threshold of 0.05), we  
263 computed the expected correlation coefficient as:

$$\mathbb{E}_{i,j}[r] = \tanh\left(\frac{1}{N} \sum_{n=1}^N \tanh^{-1}(\text{corr}(m(i)_n, m(j)_n))\right),$$

264 where  $m(x)_n$  represents column  $x$  of the bootstrapped data matrix for iteration  $n$ ,  $\tanh$  is the  
265 hyperbolic tangent, and  $\tanh^{-1}$  is the inverse hyperbolic tangent.

266 **Reverse correlation analyses**

267 We sought to characterize potential associations between the history of participants’ fitness-related  
268 activities leading up to the time they participated in a memory task and their performance on

269 the given task. For each fitness-related variable, we constructed a timeseries matrix whose rows  
270 corresponded to timepoints (sampled once per day) leading up to the day the participant accepted  
271 the HIT for our study, and whose columns corresponded to different participants. These matrices  
272 often contained missing entries, since different participants' Fitbit devices tracked fitness-related  
273 activities differently. For example, participants whose Fitbit devices lacked heart rate sensors  
274 would have missing entries for any heart rate-related variables. Or, if a given participant neglected  
275 to wear their fitness tracker on a particular day, the column corresponding to that participant  
276 would have missing entries for that day. To create stable estimates, we smoothed the timeseries of  
277 each fitness measure using a sliding window of 1 week. In other words, for each fitness measure,  
278 we replaced the "observed value" for each day with the average values of that measure (when  
279 available) over the 7 day interval ending on the given day.

280 In addition to this set of matrices storing timeseries data for each fitness-related variable, we also  
281 constructed a memory performance matrix,  $M$ , whose rows corresponded to different memory-  
282 related variables, and whose columns corresponded to different participants. For example, one  
283 row of the memory performance matrix reflected the average proportion of words (across lists)  
284 that each participant remembered during the immediate free recall test, and so on.

285 Given a fitness timeseries matrix,  $F$ , we computed the weighted average and weighted standard  
286 error of the mean of each row of  $F$ , where the weights were given by a particular memory-related  
287 variable (row of  $M$ ). For example, if  $F$  contained participants' daily step counts, we could use  
288 any row of  $M$  to compute a weighted average across any participants who contributed step count  
289 data on each day. Choosing a row of  $M$  that corresponded to participants' performance on the  
290 naturalistic recall task would mean that participants who performed better on the naturalistic recall  
291 task would contribute more to the weighted average timeseries of daily step counts. Specifically,  
292 for each row,  $t$ , of  $F$ , we computed the weighted average (across the  $S$  participants) as:

$$\bar{f}(t) = \sum_{s=1}^S \dot{m}(s)F(t,s),$$

293 where  $\dot{m}$  denotes the normalized min-max scaling of  $m$  (the row of  $M$  corresponding to the chosen

294 memory-related variable):

$$\hat{m} = \frac{m}{\sum_{s=1}^S \hat{m}(s)},$$

295 where

$$\hat{m} = (1 - \epsilon) \frac{m - \min(m)}{\max(m) - \min(m)} + \epsilon.$$

296 Here,  $\epsilon$  provides a lower bound on the influence of the lowest-weighted participant's data. We  
297 defined  $\epsilon = 0.001$ , ensuring that the lowest-weighted participant had relatively low (but non-zero)  
298 influence.

299 We computed the weighted standard error of the mean as:

$$\text{SEM}_m(f(t)) = \frac{\left| \sum_{s=1}^S (F(t, s) - \bar{f}(t)) \right|}{\sqrt{S}}.$$

300 When a given row of  $F$  was missing data from one or more participants, those participants were  
301 excluded from the weighted average for the corresponding timepoint and the weights (across all  
302 remaining participants) were re-normalized to sum to 1. The above procedure yielded, for each  
303 memory variable, a timeseries of average (and standard error of the mean) fitness tracking values  
304 leading up to the day of the experiment.

## 305 Results

306 Before testing our main hypothesis we examined the behavioral data from each of four memory  
307 tasks: a random word list learning “free recall” task; a naturalistic recall task whereby participants  
308 watched a short video and then recounted the narrative; a foreign language “flashcards” task; and  
309 a spatial learning task. Each of the first three tasks (free recall, naturalistic recall, and the flashcards  
310 task) included both an immediate (short term) memory test and a delayed (long term) memory test.  
311 The spatial learning task included only an immediate test. Participants in all four tasks exhibited  
312 general trends and tendencies that have been previously reported in prior work. We were also  
313 interested in characterizing the variability in task performance across participants. For example,

314 if all participants exhibited near-identical behaviors or performance on a given task, we would be  
315 unable to identify how memory performance on that task varied with mental health or exercise.

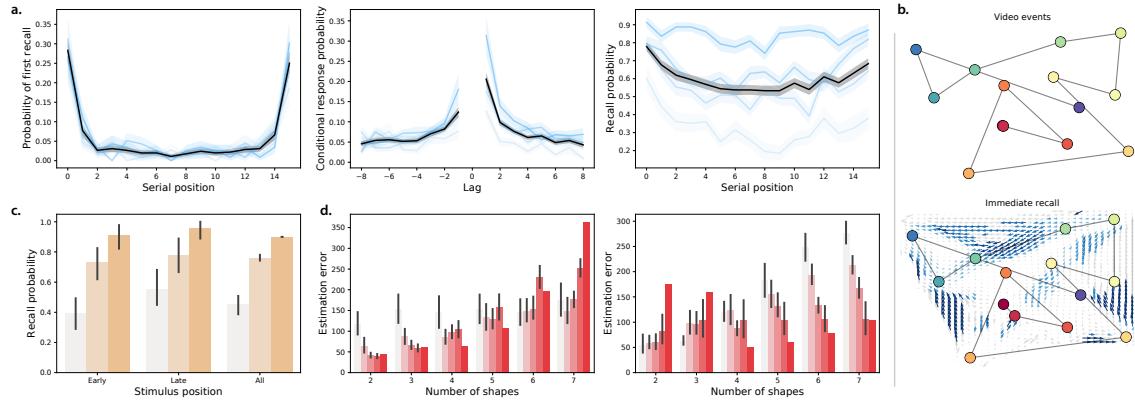
316 When participants engaged in free recall of random word lists, they displayed strong primacy  
317 and recency effects (Murdock, 1962) on the immediate memory tests (as reflected by improved  
318 memory for early and late list items; Fig. 2a, left and right panels). On the delayed memory test,  
319 the recency effect was substantially diminished (Fig. 3a, left and right panels), consistent with  
320 myriad previous studies (for review see Kahana, 2012). Participants also tended to cluster their  
321 recalls according to the words' study positions (Kahana, 1996) on both the immediate (Fig. 2a,  
322 middle panel) and delayed (Fig. 3a, middle panel) memory tests.

323 When participants engaged in naturalistic recall by recounting the narrative of a short story  
324 video, they reliably and accurately remembered the major narrative events on both the immediate  
325 (Fig. 2b) and delayed (Fig. 3b) tests. This is consistent with prior work showing that memory for  
326 rich narratives is both detailed and accurate (Chen et al., 2017; Heusser et al., 2021).

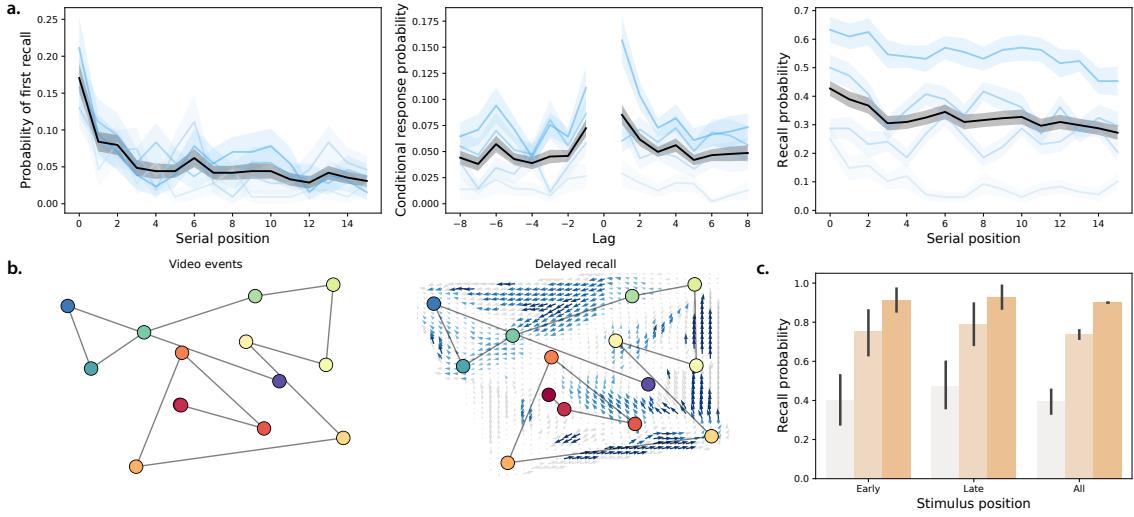
327 Performance on the foreign language flashcards task (immediate: Fig. 2c; delayed: Fig. 3c)  
328 varied substantially across participants, and did not show any clear serial position effects. Participants  
329 also displayed substantial variation in performance on the spatial learning task (Fig. 2d).  
330 In general, participants reported the shape's positions more accurately when there were fewer  
331 shapes. However, both the baseline estimation accuracy and the rate of decrease in accuracy as a  
332 function of increasing number of memorized locations varied substantially across participants.

333 In addition to observing substantial across-participant variability in memory performance,  
334 we also observed substantial variability in participants' fitness and activity metrics (Fig. 4). We  
335 examined recent measurements, averaged over the week prior to testing (Fig. 4a), baselined mea-  
336 surements (average over the prior week, divided by the average over the preceding 30 day; Fig. 4b),  
337 along with more gradually varying measures that tended to remain relatively static over timescales  
338 of weeks to months (Fig. 4c). Figure S6 displays across-participant distributions for a broad selec-  
339 tion of these measures, and Figures S7, S8, S9, and S10 show different participants' fitness metrics,  
340 broken down by their performance on different memory tasks.

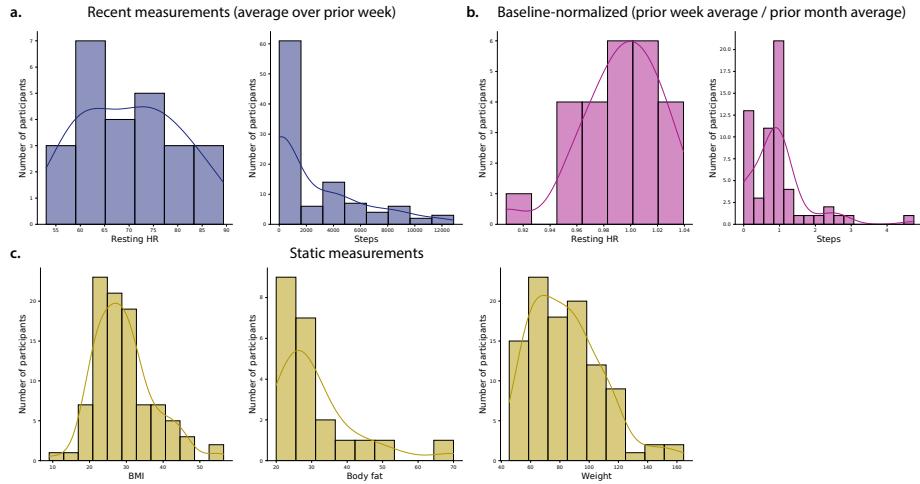
341 We wondered about potential links between the different aspects of participants' data. For



**Figure 2: Immediate memory tests.** **a. Free recall.** Left: probability of recalling each word first as a function of its presentation position. Middle: probability of transitioning between successively recalling the word presented at position  $i$ , followed by word presented at position  $i + \text{Lag}$ . Right: probability of recalling each word as a function of its presentation position. See Figure S2 for additional details. **b. Naturalistic recall.** Top: 2D embedding of a 2.5 min video clip; each dot reflects a narrative event (red denotes early events and blue denotes later events). Bottom: 2D embedding of the averaged transcripts of participants' recounts (dots: same format as top panel). The arrows denote the average trajectory directions through the corresponding region of text embedding space, for any participants whose recounts passed through that region. Blue arrows denote statistically reliable agreement across participants ( $p < 0.05$ , corrected). See Figure S3 for additional details. **c. Foreign language flashcards.** Each bar denotes the average proportion of correctly recalled Gaelic-English word pairs from early (first 3), late (last 3), or all (i.e., all 10) study positions. See Figure S4 for additional details. **d. Spatial learning.** Average estimation error in shape locations as a function of the number of shapes. See Figure S5 for additional details. All panels: error bars and error ribbons denote bootstrap-estimated 95% confidence intervals. Shading (saturation) denotes results for different subsets of participants assigned based on their task performance (Figs. S2, S3, S4, and S5 provide information about which performance metrics and values the shading reflects; in general more saturated colors denote participants who performed better on the given task.) In Panel d, participants are grouped in two ways; in the left panel, participants are grouped according to the  $y$ -intercepts of regression lines (estimation error as a function of the number of shapes); in the right panel, participants are grouped according to the slopes of the same regression lines.



**Figure 3: Delayed memory tests.** **a. Free recall.** These panels are in the same format as Figure 2a, but they reflect performance on the delayed free recall task. For additional details see Figure S2. **b. Naturalistic recall.** These panels are in the same format as Figure 2b, but the right panel reflects performance on the delayed naturalistic recall task. For additional details see Figure S3. **c. Foreign language flashcards.** This panel is in the same format as Figure 2c, but it reflects performance on the delayed flashcards test. For additional details see Figure S4.



**Figure 4: Fitness measures.** **a. Recent measures.** Resting heart rate (HR) and daily step counts, averaged over the week prior to testing. **Baseline-normalized measures.** Resting heart rate and daily step counts averaged over the week prior to testing, divided by the average resting heart rate and step counts averaged over the preceding month. **Static measures.** Body mass index (BMI), body fat percentage, and weight (in kg). For more information see Figures S6, S7, S8, S9, and S10.

example, if people who exercised in a particular way also tended to perform better on a given memory task, this could suggest that either (a) some property intrinsic to participants who exercised in a particular way might also affect their memory performance on the given task, and/or (b) particular exercise behaviors could have a causal impact on memory performance. We carried out an exploratory analysis whereby we used a bootstrap-based approach (see *Exploratory correlation analyses*) to identify reliable correlations between different aspects of memory performance (Fig. S11), different aspects of fitness (Fig. S12), different demographic attributes (Fig. S13), and correlations between memory performance, fitness information, and demographic attributes (Fig. S14). Several patterns emerged. First, we found that participants' performance on the (within-task) immediate versus delayed memory tests from the free recall, naturalistic recall, and foreign language flashcards tasks were positively correlated ( $rs > 0.25, ps < 0.003$ ). This suggests that, within each of these tasks, similar processes or constraints may influence both short term and long term information retrieval. We also found reliable across-task correlations between participants' (immediate and delayed) performance on the free recall and foreign language flashcards tasks ( $rs > 0.3, ps < 0.03$ ).

A large number of fitness-related measures displayed reliable correlations (for a complete report, see Fig. S12). For example, body mass index (BMI) and weight were correlated ( $r = 0.91, p < 0.0001$ ). Resting heart rate over the prior week was negatively correlated with recent low-to-moderate-intensity ("fat burn") cardiovascular activity levels ( $r = 0.70, p = 0.0004$ ). Participants' peak heart rate (averaged over the prior week) were also negatively correlated with recent increases in step counts and daily elevation gains ( $rs < -0.26, ps < 0.03$ , bootstrap corrected), where recent changes were defined as the average values over the seven days leading up to the test day divided by the average values over the preceding 30 days. Although several demographic attributes (Fig. S13) displayed trivial correlations (e.g., participants identifying as male never reported identifying as female, and so on), we also observed a negative correlation between reported stress and alertness ( $r = -0.44, p < 0.0001$ ), and positive correlations between the reported clarity of the instructions for all tasks ( $rs > 0.26, ps < 0.02$ ).

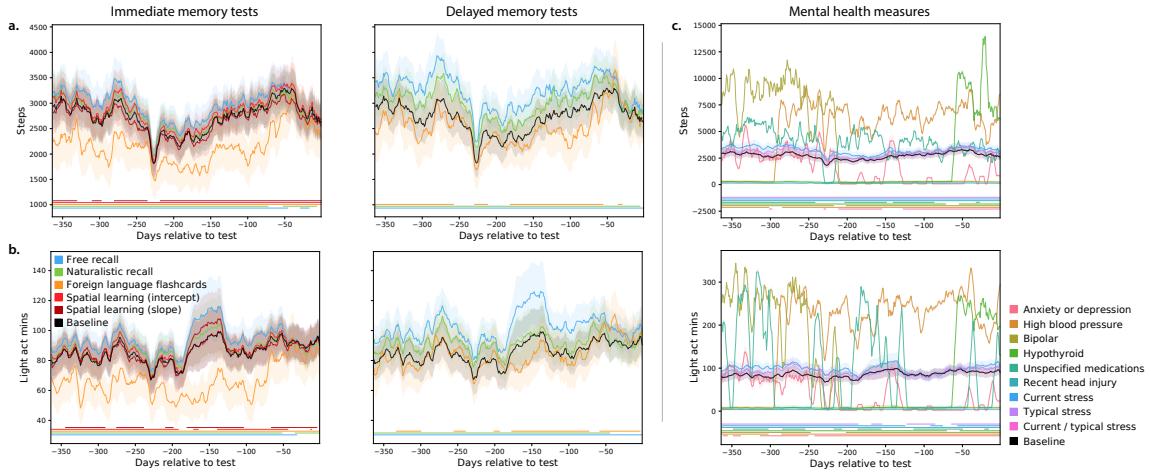
We also found reliable correlations between participants' fitness and demographic measures

Behavioral measures	Mental health measures									
	Anxiety or depression	High blood pressure	Bipolar	Hypothyroid	Unspecified medications	Recent head injury	Current stress	Typical stress	Current / typical stress	Alertness
Free recall (immediate)		-0.11	0.11	-0.16	0.16	-0.05				
Free recall (delayed)			0.20	-0.16	0.10	-0.13		0.17		
Naturalistic recall (immediate)	0.07	0.12	-0.25			0.05				
Naturalistic recall (delayed)	-0.06	0.12	-0.15	0.10	-0.10					
Foreign language flashcards (immediate)	0.11				0.09	0.17				
Foreign language flashcards (delayed)		0.15		0.15			-0.29		-0.15	
Spatial learning (intercept)	0.02		-0.14	-0.10						
Spatial learning (slope)	0.04		-0.03	0.04	0.13				-0.19	

**Figure 5: Memory performance differs according to mental health measures.** The reported values in the table reflect correlations between each behavioral measure and mental health measure. Only statistically reliable correlations ( $p < 0.05$ , corrected) are displayed. We used participants' mean recall accuracy to characterize performance on the free recall and foreign language flashcards tasks, and mean precision to characterize performance on the naturalistic recall tasks. We characterized performance on the spatial learning task using the (inverted and normalized) intercepts and slopes of linear regressions on mean estimation errors as a function of the number of studied shapes (also see Figs. 2, 3, S2, S3, S4, and S5). Typical and current stress levels were measured by self report. Mental health information was inferred using each participants' list of self-reported medications.

and their behaviors in different tasks (for a complete report, see Fig. S14). For example, recent low-to-moderate-intensity (“fat burn”) cardiovascular activity was positively correlated with immediate ( $r = 0.38, p = 0.03$ ) and delayed ( $r = 0.38, p = 0.029$ ) recall on the naturalistic memory task. Recent increases in moderate-intensity (“cardio”) activity over the prior 7 days (relative to the preceding 30 days) was also positively correlated with immediate naturalistic recall ( $r = 0.48, p = 0.003$ ) and immediate recall on the foreign language flashcards task ( $r = 0.43, p = 0.048$ ). Recent high-intensity (“peak”) activity was positively correlated with performance on the spatial learning task ( $r = 0.34, p < 0.0001$ ), as were recent increases in high-intensity activity (prior 7 days versus preceding 30 days;  $r = 0.41, p = 0.01$ ). Mental health indicators, such as self-reported stress levels and medications were also associated with differences in memory (Figs. 5, S14). For example, self-reported stress levels at the time of test were negatively correlated with performance on the delayed memory test for the foreign language flashcards task ( $r = -0.29, p = 0.038$ ), whereas participants who were medicated for anxiety and depression tended to perform slightly (but reliably) *better* on the immediate memory test for the foreign language flashcards task ( $r = 0.11, p < 0.0001$ ).

The above analyses indicate that recent differences in fitness-related activity are associated with differences in memory performance and mental health measures. Although the analyses treated these measures on average or in aggregate, many of the measures we collected are dynamic. For example, the amount or intensity of physical exercise people engage in can vary over time, and so on. We wondered whether the dynamics of fitness-related measures might relate to memory performance and mental health measures. To this end, we carried out a series of reverse correlation analyses (see *Reverse correlation analyses*) to examine whether participants with different cognitive or mental health profiles also tended to display differences in fitness-related measures over time. In particular, we examined fitness data collected from participants’ Fitbit devices over the year prior to their test day in our study. Several example findings are summarized in Figure 6. We found that participants who performed well on the immediate and delayed free recall memory tests and on the naturalistic recall tests tended to be more active than participants who performed poorly on those tests (Figs. 6a, b; S15). Conversely, participants who performed well on the immediate and delayed foreign language flashcards tasks tended to be *less* active. These differences were



**Figure 6: Dynamics of physical activity varies with memory performance and mental health measures.** **a. Daily step counts.** Each timecourse is weighted by either performance on immediate recall tests (left panel) or on delayed recall tests (right panel). The black (baseline) timecourses display the (unweighted) average across all participants. **b. Daily duration (in minutes) of low-intensity physical activity.** Timecourses are displayed in the same format and color scheme as those in Panel A. **c. Timecourses of physical activity, weighted by mental health measures.** The timecourses in each panel display the average daily step counts (top panel) or duration of low-intensity activity (bottom panel). Each color denotes the average timecourse for all participants with the indicated mental health conditions. The baseline curves (black) display the average across all participants (re-plotted in Panel C to illustrate scale differences across panels). Error ribbons in all panels denote the standard error of the mean. Horizontal lines below each panel's timecourses denote intervals over which each weighted measure (color) differs from the unweighted baseline.

398 present even a full year before the testing day. We also found substantial variability across people  
399 with different (self-reported) mental health profiles (Figs. 6c, S18). Due to small sample sizes of  
400 individuals exhibiting several mental health dimensions, it is difficult to distinguish generalizable  
401 trends from individual differences that one or two individuals happened to exhibit. However,  
402 several large-sample-size trends emerged. For example, participants who reported higher levels  
403 of stress also tended to be slightly more physically active than participants who reported lower  
404 stress levels. We found analogous differences in other activity-related measures (Figs. S15 and  
405 S18), cardiovascular measures (Figs. S16 and S19), and sleep-related measures (Figs. S17 and S20).  
406 Taken together, the analyses suggest that cognitive and mental health differences are also associated  
407 with differences in the dynamics of physical health measures.

## 408 Discussion

- 409     • summarize key findings
- 410     • correlation versus causation
- 411     • what can vs. can't we know? we can identify correlations, but not causal direction– e.g. we  
412         cannot know whether exercise *causes* mental changes versus whether people with particular  
413         neural profiles might tend to engage in particular exercise behaviors. that being said, we *can*  
414         separate out baseline tendencies (e.g., how people tend to exercise in general) versus recent  
415         changes (e.g., how they happened to have exercised prior to the experiment).
- 416     • related work (exercise/memory, exercise/mental health), what this study adds
- 417     • future direction: towards customized physical exercise recommendation engine for optimiz-  
418         ing mental health and mental fitness

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<sup>425</sup> of this work. Dave served as a mentor and colleague on the project prior to his passing.

<sup>426</sup> **Data and code availability**

<sup>427</sup> All analysis code and data used in the present manuscript may be found [here](#).

<sup>428</sup> **Author contributions**

<sup>429</sup> Concept: J.R.M. Experiment implementation and data collection: G.M.N. Analyses: G.M.N., E.C.,  
<sup>430</sup> P.C.F., and J.R.M. Writing: J.R.M.

<sup>431</sup> **Competing interests**

<sup>432</sup> The authors declare no competing interests.

<sup>433</sup> **References**

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